COGGING TORQUE REDUCTION OF SEGMENTED HEFSM USING COMBINED TECHNIQUE OF NOTCHING AND CHAMFERING FOR PERFORMANCE IMPROVEMENT

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This dissertation is dedicated to my beloved father NABI BUX SHAIKH and my mother late RABIA SHAIKH. My brothers, and sisters, who have always encouraged me with their love and prayers.

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ABSTRACT

Cogging torque is one of the factors which affect the motor in terms of vibration and non-audible noise that become serious issue in flux switching machines. It is mandatory for every motor to have low cogging torque because having low cogging torque enhancing the control based on positioning of the motor in electric vehicle drive application. This project focus on reducing the cogging torque of segmented rotor HEFSM having 24S-8P using various rotor techniques configuration such as notching (NOT) and chamfering (C.H), were examined. Then a new technique has been proposed and compared using combination of NOT and C.H for reduction of cogging torque. The new proposed design configuration has been executed using 2D commercial JMAG version 15.1 at no load and load conditions for analysing the best results. Initially techniques based on NOT and C.H has reduced the cogging torque by 46% and 57% respectively of the original value of 9.5Nm. Then a new proposed technique of combination of NOT and C.H reduced almost by 60% of the initial result simultaneously. This result is considered as the best reduced technique for reduction of cogging torque of segmented HEFSM. The performance of HEFSM segmented rotor 24S-8P has been increased by using "local optimization method" based on parameter sensitivity. The total performance torque is achieved almost 55% more than the initial torque 11.07Nm. The combined technique of NOT and C.H has successfully reduced the cogging torque which improves the motor performance in terms of acoustic noise and vibration.

ABSTRAK

Tork penunggalan adalah salah satu faktor yang memberi afek kepada motor dari segi getaran dan bunyi akustik secara tidak langsung menyebabkan isu parah dalam FSM. Ia adalah mandatori bagi setiap motor untuk menghasilkan tork penunggalan yang rendah kerana tork penunggalan yang rendah mampu mempertingkatkan sistem kontrol berdasarkan kedudukan motor didalam aplikasi pengendali kenderaan elektrik. Secara permulaan, projek ini berdasarkan penurunan tork penunggalan rotor bersegmen HEFSM yang mempunyai 24S-8P dengan mengunakan pelbagai teknik konfigurasi rotor seperti Mencatat (NOT), Chamfering (C.H) yang telah dikenalpasti. Oleh itu, teknik baru dicadangkan dan bandingkan menggunakan kombinasi antara NOT dan C.H bagi menggurangkan tork penunggalan. Reka bentuk konfigurasi yang baru dicadangkan itu dilaksanakan dengan menggunakan perisian komersial 2D JMAG versi 15.1 pada keadaan mempunyai beban dan tiada beban bagi menganalisa keputusan yang terbaik. Pada mulanya, teknik ini berdasarkan NOT dan C.H telah mengurangkan tork penunggalan masing-masing sehingga 46% dan 57% dari nilai asal iaitu 9.5 Nm. Oleh yang demikian, teknik baru yang dicadangkan iaitu kombinasi NOT dan C.H telah berjaya menggurangkan hampir 60% dari nilai asal penemuan. Penemuan ini dipandang tinggi sebagai teknik terbaik untuk menggurangkan tork penunggalan segmen HEFSM. Prestasi penemuan HEFSM rotor bersegmen 24S-8P telah dipertingkatkan dengan menggunakan “local optimization method” berasaskan kepekaan parameter. Hasil jumlah prestasi tork yang dicapai ialah hampir 55% lebih tinggi berbanding nilai asal tork iaitu 11.07 Nm. Kombinasi teknik NOT dan C.H telah berjaya menggurangkan tork penunggalan dimana menambah-baik prestasi motor dari istilah bunyi akustik dan getaran.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Alternating Current
F	-	Frequency [Hz], [rad/s]
J	-	Current Density [A/m^2]
N	-	Number of turns
P	-	Number of Poles
RPM	-	Revolution Per Minute
T	-	Torque [Nm]
EMF	-	Electromotive Force
FEA	-	Finite Element Analysis
FEC	-	Field Excitation Coil
SM	-	Synchronous Motor
FSM	-	Flux Switching Motor
FEFSM	-	Field Excitation Flux Switching Motor
PMFSM	-	Permanent Magnet Flux Switching Motor
HEFSM	-	Hybrid Excitation Flux Switching Motor
NOT	-	Notching
C.H	-	Chamfering
IMs	-	Induction Motor
SRM	-	Switch Reluctance Motor
HEV	-	Hybrid Electrical Vehicles

CHAPTER 1

INTRODUCTION

1.1 Research Background

Electric machine is a vast technology based on the electric motors and electric generators which uses the electromagnetic forces. In the period of electric machines, much of the insights in the proceeding discussion is applicable to the motoring class of electrical machines which is estimated to account for 60-70% of the electrical energy utilization in the developed world [1, 2]. The strategy for electric motors has led to design a new type of motor called flux switching motor, which has ability to get energy efficient with low cost and reduces the cogging torque. A flux switching motor is one of the developments, deals with economic and environmental pressures [3].

The first idea of flux switching machine (FSM) was founded and published in the mid of 1950s.The overall mechanism of Flux switching motor (FSM) based on stator and rotor, although the sources of flux shifted to stator side thus the rotor is considered as free to move. The manufacturing of Flux switching motor is easy because the structure having only single piece of iron at the rotor side, and this arrangement of design keeps the motor robust as well as efficient in terms of high speed in operations.

Permanent magnet flux switching machine (PMFSM) firstly came in platform as part of flux switching machine that is permanent magnet (PM) also known as Laws relay. It is single phase limited angle actuator, having 4 stator slots and 4 rotor poles was developed, meanwhile it was further changed to single phase generator based on4 stator and 4 or 6 rotor poles. It has been observed over the last ten years regarding development of FSM topologies for different applications, ranging from low cost domestic appliances, automotive, wind power, aerospace, and others [4]. This kind of development has major advantages, where the winding of synchronous machine has shifted to stator side and there will be no attachment of brushes. This mechanism brings all control operated over the field flux. The motor is operated by the help of switching flux. Flux switching machine is working on the basis of combined principle of switched reluctance machine (SRM) and induction generator. The fundamental of operating the FSM is by changing the polarities of induced flux that makes contact with the armature winding with change of rotor position [5].

Flux switching machine is classify into three parts, firstly the permanent magnet flux switching machine (PMFSM) has PM used as main source of flux, secondly the field excitation flux switching machine (FEFSM) has field excitation coil called FEC used as main source of flux, and third is combination of PMFSM and FEFSM known as hybrid excitation flux switching machine (HEFSM).

Hybrid excitation flux switching motor has driven by two sources of excitation, the PM source called as primary excitation and FEC called secondary excitation in terms of DC field excitation coil. The performance of PMFSMS has comparatively poor weakening flux, however in terms of controlling the current of armature winding it can be operated in the poor flux region. When the negative d-axis current is applied, the field of PM can be countered but the copper losses can be increased and can reduce the efficiency as well as reduce capabilities of power, and the irreversible demagnetization can be possible. So HEFSM having rotor segmented is an alternative option for getting strong flux by using the PM and DC FEC sources at the stator side as shown in Figure 1.1 [8].

HEFSM has greater evaluation in terms of research over many years in order to improvise performance of flux weakening, capabilities of variable flux and power as well as torque density [6, 7]. HEFSM with segmental rotors are used as beneficial for controlling the saliency ratio, the fundamental of segments is to provide the magnetic path for field flux which links with stator armature coils as rotor rotates. The actual problem in segmental rotor flux switching (SRFS) motor is torque ripples which has 50 percent of total average that produces in field and armature current. This ripple has occurred because of the attraction of magnet on surface of the rotor and stator teeth cause cogging torque which creates vibration, distortion, and non-audible noise. The main reason of such designs of HEFSM not only reduces the cost of material but can reduce the cogging effect as well improving the performance of motor.

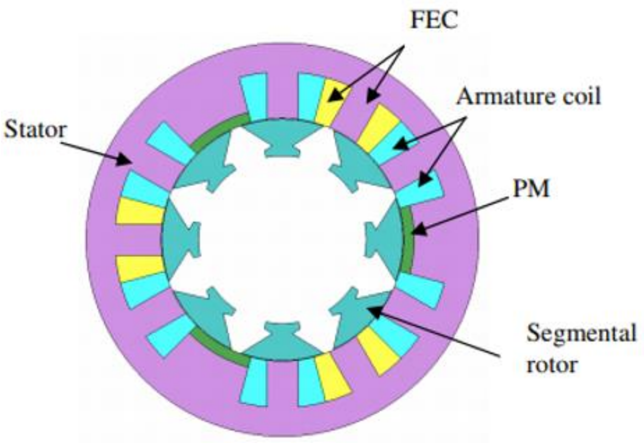


Figure 1.1: Design Structure of 12S-8P HEFSM with Segmental rotor [8]

1.2 Problem Statement

In recent development, the use of HEFSM is alternating option where the advantages of FE and PM machines are combined. Moreover, rotor with segments has been used in novel way to produce bi polar flux linkages in the armature windings to achieve the high torque densities.

However, in HEFSM machines, the opposite direction of FE and PM fluxes cause the effect of flux cancellation in result reduces the overall performance of machine [8]. Besides, HEFSM suffers from higher torque ripples up to 40% because it carries PM sources at the stator side hence it increases the cogging torque [8]. Therefore, a new design of HEFSM with segmental rotor is proposed in which number of magnets slots have been increased and arrange in a manner to avoid the flux cancellation between FE and PM fluxes and produce smooth flux distribution on the stator and rotor side.

Furthermore, the arrangement of magnet slots and rotor segments of proposed design can reduce the cogging torque which helps to increase the overall performance of machine with high efficiency and less loss.

1.3 Objectives of the Study

The objective of this research is based on designing the HEFSM with segmental rotor by using 2D Finite Element Analysis (FEA). By the use of JMAG designer 14.1, there are some major objectives which have to be achieved such as;

(i) To design and investigate performances of HEFSM using various segmented rotor modification.

(ii) To analyse the performances of improved segmented HEFSM at no load using notching (Not), chamfering (C.H) and their combination for cogging torque reduction.

(iii) To optimize the performance of improved design of segmented HEFSM using "Local optimization" based on parameter sensitivity.

1.4 Scope

(i) This project is design by using JMAG Designer version 15.1. JMAG is research tool, which is capable of doing simulation on the basis of designs and electrical machines.

(ii) Cogging torque minimisation technique is used by using 2D-FEA solver by JMAG Designer 15.1, released by Japan Research Institute (JRI). The range of current density for FEC is maintained at maximum level (30A/mm^2), respectively. Cogging torque characteristics will be examined at open circuit.

(iii) The range of current density for FEC and Armature winding is maintained at the maximum level (30 A/mm^2) and (30 A_{rms}/mm^2).

1.5 Project Outline

This project outline comprises on five chapters and the briefing of the chapter is described in given below:

(i) Chapter 1: Introduction

In starting of first chapter, project gives some brief detail about the research including the introduction of HEFSM, problem based on previous research related to HEFSM, the effect of cogging torque of HEFSM, objectives of research and scope.

(ii) Chapter 2: Literature Review

This section based on literature review that summarizes the basics of FSM and cogging torque of electrical machines. Techniques regarding cogging torque reduction of different salient rotor poles and the process of optimization of FSM are discussed in detail.

(iii) Chapter 3: Methodology

This section gives introduction on implementation of the research that is categorized into three parts including implemented design of HEFSM, new technique of reducing cogging torque and finally the optimization. The Design part is further divided into sessions which are geometry editor and JMAG-Designer. Then the new technique will be used for reducing cogging torque at no load condition at maximum 30A/mm^2 for FEC. And in last the "Deterministic Optimization" process will be used one by one to all parameters of design until the peak value of torque is achieved respectively.

(iv) Chapter 4: Results and Discussion

This section describes the proposed design of HEFSM with segmented rotor performance by doubling the FE and PM at the stator side at load condition and no-load condition by using 2D-FEA. By using different techniques to validate the performance of reduction of cogging torque, the design was examined under the no load condition, then the best method is achieved for reducing cogging torque. And in finally by using the optimization process the performance is getting better in terms of performance torque compared to initial results, flux distribution at closed circuit.

(v) Chapter 5: Conclusion and Future Work

This final section gives detail of the whole thesis based on results regarding the performances and targets as compared with a previous work and also suggest for the future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The electric motor is one of the biggest developments throughout the world in the field of advancement technology of engineering in the generation of electricity [8]. Electric motor is a device which has electro-mechanical mechanism that converts electrical energy into mechanical energy. The fundamental principle of electric motor is that when current carrying conductor is placed in between the magnetic field, it creates interaction between the field and current. As the conductor carries current in the presence of magnetic field it experiences a force that tends the armature to rotate. This current mainly induces due to presence of magnetic field and current. According to the basic principle based on torque which is produced due to reaction between field flux and armature current cause rotor to rotate as well as induced voltage of DC motor shown in Equation (2.1) and Equation (2.2). Moreover, the quality of work regarding advancement of motor invention has taken place as extreme level of job for upcoming engineers [9-10].

$$E = E_b + I_a R_a \tag{2.1}$$

$$T = K_a \phi I_a \tag{2.2}$$

Where E called the applied voltage, Eb called motor back emf also known as voltage speed, Ra called armature current and Ia called armature resistance, T is called developed torque, Ka is called constant and flux is denoted with ϕ. AC motor is categorized into three parts namely induction motor, switch reluctance motor and synchronous motor is shown in Figure 2.1.

Induction motor also called asynchronous motor is an AC motor comprises on stator which is stationary and rotor in which the sources of electromagnetic induction has taken by means of magnetic field to produce torque by giving electric current on the rotor. Basically, the applications of induction motor are usually used in home and industrial area especially in the field of variable speed operations. There is no physically appearance of wiring in the induction motor that's why the voltage in induced in the rotor winding rather than using any wire outside [11-12]. Induction motor does not require dc field to run the motor because it operates on the connectivity of induced current of rotor winding and air gap that built in between the rotor and stator at the time of manufacturing [13].

Switch Reluctance motor is also called stepper motor, is an electric motor which has winding on the stator side and motor possess no winding, this is specialty of switch reluctance motor in terms of design manufacturing that the power is to be delivered to a stator side. Nasarin is the one, who give first reference of SRMs in 1980s and became prevalent onwards, SRMs is also gone through acoustic noise that produced due to salient structure in rotor and stator side [14].

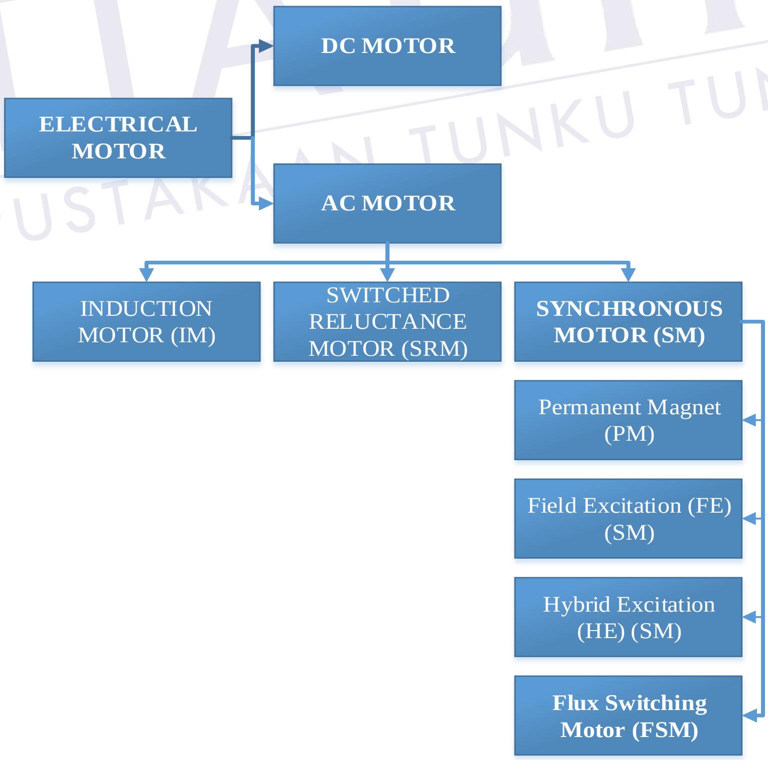


Figure 2.1: Categorization of Electric Motors

The motor which has property of synchronism called Synchronous Motor, the mechanism of SMs based on stator and rotor in which three phase of supply has provided externally to stator winding and DC supply is given to rotor respectively. This three-phase supply produce rotating magnetic field which makes alignment with magnetic field of rotor hence the motor runs under the frequency of synchronism. The given Equation (2.3) and Equation (2.4) describes on the conditions in which the synchronous motor works [14].

$$S = \frac{120\ f}{p} \tag{2.3}$$

$$v = RI + \frac{d\emptyset}{dt} \tag{2.4}$$

where S is the speed of rotor, f is frequency, P is number of poles, I is the current and ϕ is the flux.

2.1.1 Flux Switching Motor (FSM)

Flux switching machine was introduced and searched at the middle of 1950s, generally flux switching machine based on stator and motor in which all the sources of excitation shifted to stator side and the manufacturing of rotor design keeps very low weight so that rotor can easily rotate moreover it does not carry any winding over rotor and works in high speed operation as well. The working principle of flux switching machine is that the external source is provided to stator and operates on the basis of faraday's law in which the induced voltage produced cause rotating magnetic field, rotating angular speed w_r, switching of flux linkages dϕ, along with position ɵ as shown in mathematical Equation (2.5) [15].

$$v = w_r \frac{d\phi}{d\theta} \tag{2.5}$$

Flux switching machine is classified into three parts;

- Permanent Flux Switching Motor (PMFSM)
- Field Excitation Flux Switching Motor (FEFSM)
- Hybrid Excitation Flux Switching Motor (HEFSM)

2.1.1.1 Permanent Magnet Flux Switching Motor (PMFSM

The construction of permanent magnet flux switching motor (PMFSM) is simple having structure of toothed rotor shown in Figure 2.2, basically PMFSM has stator part in which PM and armature winding are carried because of this design of stator it is easy to provide cooling system for application based on high speed configuration [16]. PMFSM is used PM as main source which can generate the induced flux whereas the production of flux is fixed which means the flux remain constant [17-19].

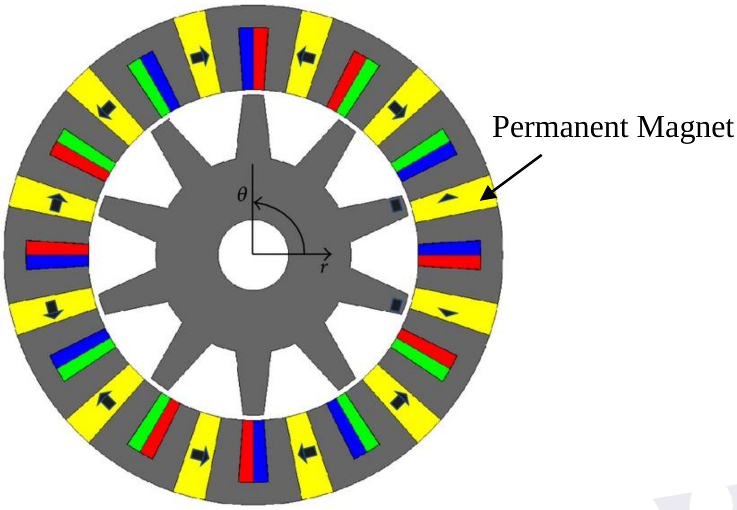
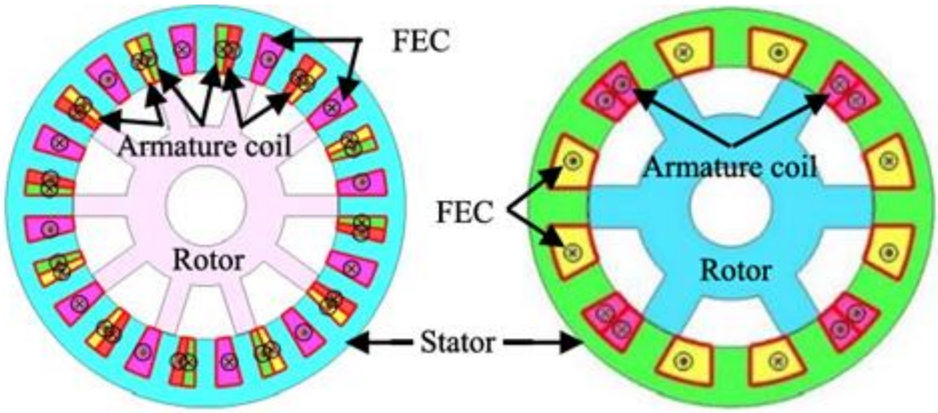


Figure 2.2: PMFSM with 12S-10P with toothed rotor

2.1.1.2 Field Excitation Flux Switching Motor (FEFSM)

Field Excitation Flux Switching Motor (FEFSM) is different in terms of source and construction compared with PMFSM for generating flux because FEFSM uses FE source as shown in Figure 2.3. Field excitation flux switching motor consist of stator made up of laminated core having FECs coils as the main source. And rotor is also composed of laminated core which makes alignment with the stator during switching to rotate. The principle of operating the motor by simply provides external DC source to energize the FEC coils to make sure the current is passing through the windings [20, 21]. The control is easier in FEFSM in terms of flux because the mechanism depends on input source. Also, the FEFSM does not require rare-earth magnet (those magnets which are capable of generating high magnetic field) in result reduction of cost [22].



(a) (b)

Figure 2.3: FEFSM with (a) 24S-10P and (b) 12S-10P with salient rotor

2.1.1.3 Hybrid Excitation Flux Switching Motor (HEFSM)

The word Hybrid referred as combination of two things same as Hybrid Excitation Flux Switching Motor (HEFSM) is taken as two source machines in which PM and FE are used as main source. In the HEFSM, PM is called primary source whereas the secondary source called Field Excitation shown in Figure 2.4. HEFSM is considered as best alternator as compared to PMFSM that has problems in terms of copper loss and use of PMs having possible effect of irreversible demagnetization. This is why HEFSM is a perfect option in which PM and FE is used together in stator side. HEFSM were introduced for improving the torque characteristics in terms of starting and low speed and to improve flux capabilities especially for the hybrid Electric Vehicle [23]. The operating principle of HEFSM can be observed in Figure 2.5, in which the direction of flux is indicated by red and blue line of both sources. The mechanism follows the indication of both source (PM and FEC) of flux that carries same polarity that move combined together in the region of rotor is shown in Figure 2.5 (a) and (b), as rotor changes the place the polarity line up with flux that induced in the rotor in the switching process and in Figure 2.5 (c) and Figure 2.5 (d), it is seen that FEC has reverse direction. The flux of PM will only move on the rotor and FEC is over stator in result less excitation.

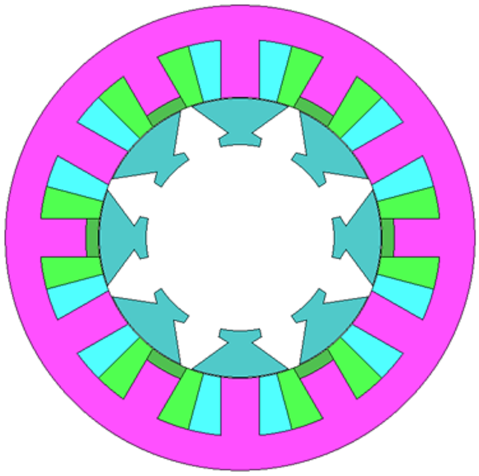


Figure 2.4: HEFSM with segmented rotor [8]

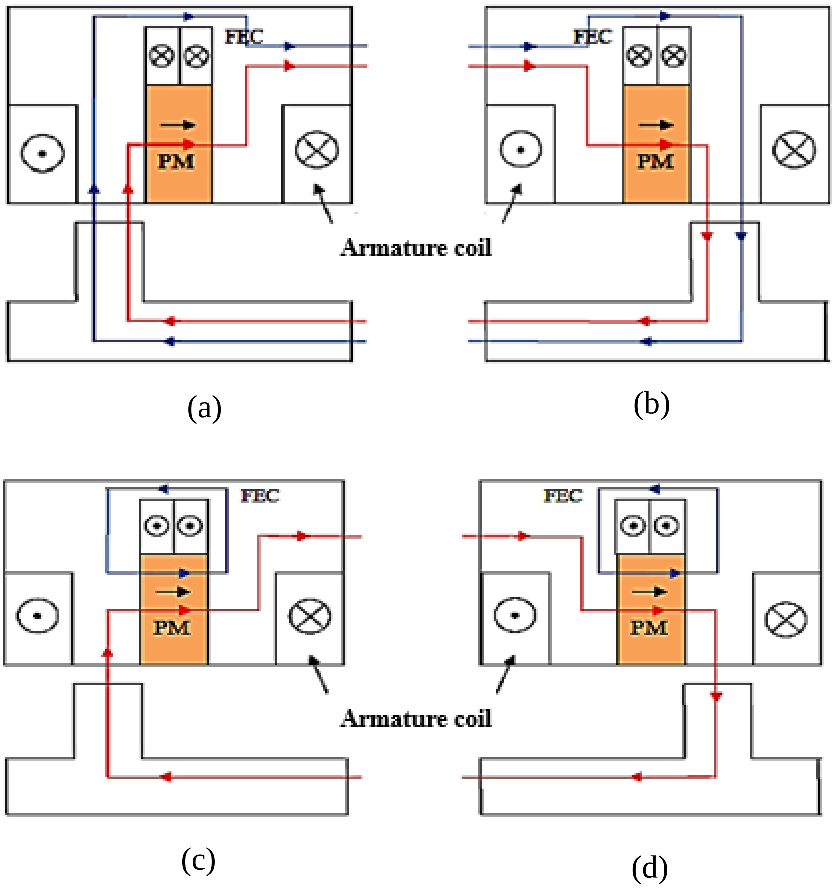


Figure 2.5: The operating principle of the proposed HEFSM (a) θe=0° - more excitation (b) θe=180° - more excitation (c) θe=0° - less excitation (d) θe=180° - less excitation [8]

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